

Research on improving energy efficiency and the annual distributing structure in electricity and gas consumption by extending use of GEHP

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ABSTRACT

The gas engine-driven heat pump (GEHP), which has been considered as a preferable choice in the heating and air-conditioning scheme can make full use of the waste heat from the engine and achieve a higher primary energy ratio (PER) than other forms of heating/cooling systems. In this paper, the relationship between the capacity characteristic of the GEHP and the heating and cooling loads of buildings has been analyzed. Meanwhile the reasons of the imbalance of the urban electricity and natural gas consumptions between summer and winter have been studied. The running characteristic of a water-to-water GEHP has been investigated experimentally and the PER was measured. Based on the analysis and experimental results, it could be concluded that if both the gas-fired boilers and electric air conditioners are replaced by GEHPs in some percentage, we can narrow the gaps between the requirement and provision of electricity and natural gas and balance the seasonal consumption differences of electricity and natural gas between summer and winter simultaneously. In order to improve energy efficiency, environmental quality and energy consumption structure effectively, the governmental incentive policies for promoting use of GEHPs should be formulated in China and some other developing countries.

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1. Introduction

1.1. Energy saving and environment friendly equipment-GEHP

Nowadays, two of the main problems in the whole world are the depletion of fossil fuels and environmental pollution (Hepbasli et al., 2009). The consumptions of coal and oil have made great contributions to the environmental pollution since the first Industrial Revolution, such as the atmospheric pollution, water pollution and solid waste pollution. China is one of the countries that use coal as the main energy resource and most of the coal is used directly for burning without coal-gasification, which has caused lots of environmental problems. Monitoring results show that 70% soot and 90% SO₂ in the atmosphere are produced by burning coal (State Planning Commission, 1993). Investigations are focused on solving these problems by two ways (Hepbasli et al., 2009), on one hand, developing alternative energy sources and related applications; on the other hand, improving energy efficiency of the equipments which consume fossil fuels. Therefore, in recent years, many countries pay more attention to the natural gas which can not only decrease the usage of coal and

oil but also reduce the environmental pollution. The relative quantities of pollutant discharge among different energy sources are shown in Table 1 (Chen and Wang, 2004).

Chinese government has made many policies on natural gas industry since 1998, for example, the policy of *National Policy on Natural Gas Utilization*. From then on, this clean energy was widely spread in many fields, such as city heating, chemical industry, automobile and power producing. At present, most of the natural gas is used in gas-fired boilers for heating to replace the coal-fired boilers, and it is inefficient to burn this precious fuel directly. Therefore, a kind of higher efficiency equipment which consumes natural gas must be developed.

GEHP is a kind of energy saving and environment friendly equipment. A GEHP usually consists of a vapor compression heat pump (HP) with an open type compressor driven by a gas engine instead of electric motors. The distinctive part of a GEHP is the gas fueled internal combustion engine system. Although the efficiency of the gas engine is not very high (about 30–45%), the waste heat can be recovered efficiently in the GEHP system. Approximately, 80% of the waste heat of fuel combustion can be recovered (Li et al., 2005b). Therefore, the considerable differences between the GEHP system and the conventional electric HP system are the heat recovery device and the higher energy efficiency. The waste heat can be recovered by utilizing the heat energy of exhaust gas and the heat energy carried by circulating

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Table 1
Relative quantities of pollutant discharge among different energy sources.

Pollutants	SO ₂	NO _x	CO	CO ₂	Ash
Natural gas	1	1	1	1	1
Oil	400	5	16	1.33	14
Coal	700	10	29	1.67	148

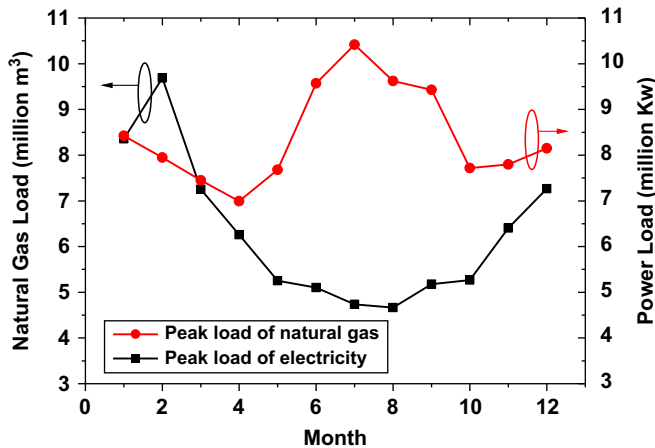


Fig. 1. The seasonal peak and valley of Shanghai electricity and natural gas consumption in 2000.

cooling water of the engine cylinder jacket. Therefore, the GEHP has a higher primary energy ratio (PER) than any other forms of heat pumps (HPs). The abbreviations of PER and COP can be defined as follows:

$$PER = \frac{\text{Heat capacity of the HP in a GEHP} + \text{The recovery of waste heat from the engine}}{\text{The heat produced by burning fuels}} \quad (1)$$

$$COP = \frac{\text{Heat capacity of the HP in a GEHP} + \text{The recovery of waste heat from the engine}}{\text{Input power of compressor}} \quad (2)$$

Although the first investigation about GEHP had been performed at late 1970s (Flurschütz, 1978; Struck et al., 1978), the first commercial GEHP was produced and accessed to market in 1985 (Ogura et al., 1987). Gradually, it has become widespread all over the world for various research and application purposes.

1.2. Seasonal differences of the natural gas consumption

In China, many cities are short of electric power in summer due to a large amount of electric air conditioners. On the contrary, the consumption of the natural gas is much smaller than its supply capacity in summer, which will lead to an additional cost for storing the excess natural gases. Therefore, the maximum of the gas consumption difference between summer and winter has been limited to a certain percentage during one year in most cities of China. Fig. 1 shows the seasonal peak and valley of electricity and natural gas consumption in Shanghai (Cheng, 2002).

From Fig. 1, we can see that the distribution of electricity and natural gas consumption is opposite from June to October. It is also the same situation in some developed countries without the extending use of the GEHP. A comparison of the electricity and natural gas consumptions with (1998) and without (1988) extending use of GEHP in a developed country of Asia is shown in Fig. 2 (Cheng, 2002). The ordinate of Fig. 2 is the gas/power load

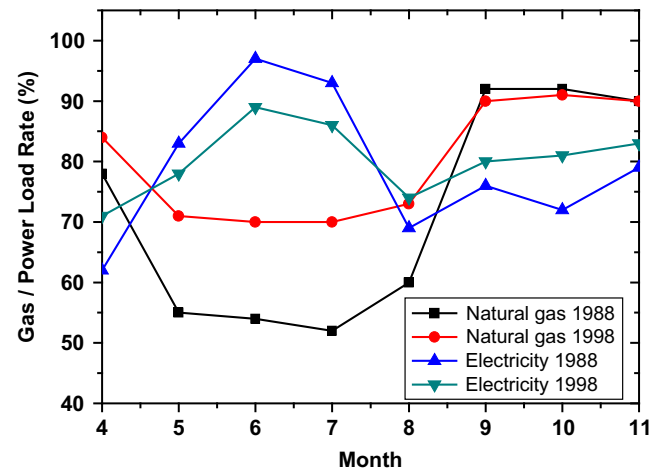


Fig. 2. The comparison of the electricity and natural gas consumption with (1998) and without (1988) extending use of GEHP in a developed country of Asia.

rate (%), the ratio of the real consumption to the supply of natural gas and electricity, respectively. From this figure we can see that the GEHP used for cooling and heating instead of gas-fired boilers and electric air conditioners could decrease the seasonal consumption imbalance of natural gas and electric power simultaneously in this developed country. And also we can see that from 1988 to 1998, with the extending use of the GEHP, the energy consumption configuration of this developed country became more reasonable.

In this paper, we would like to prove that favorable policies for extending use of the GEHP can play an important social and economic role in developing countries, such as China. The

popularization use of the GEHP could balance the electricity and natural gas consumptions between summer and winter, and could also cut the peak of electricity consumption and fill the valley of gas consumption in summer. Suitable energy consumption policies are helpful for improving the energy consumption configuration of the countries.

1.3. Current literature survey of the GEHP technologies

Literature surveys clearly show that many studies have been done on the technologies of the GEHP. Most investigators had devoted their attention to the following aspects:

- (1) *Integral energy efficiency and economic analysis:* Yang et al. (2003) investigated the operating characteristics of a GEHP system experimentally. The performances of the gas engine and heat pump system of the GEHP system were measured under different working conditions. The results showed that the GEHP had a good energy saving performance and the PER of the system achieved 1.42 under the experimental operating condition. Guo et al. (2005) also studied on the performance of a GEHP including the relationship between the gas engine efficiency and the compressor performance. The engine efficiency and the PER of the system were taken to judge the economy of the GEHP. Aiming at the economy of system, the

economic performances of a gas engine and a GEHP system were analyzed respectively. At the same time, the effective method of improving the economy of the GEHP system was analyzed.

- (2) *Investigations on improving the performance of the GEHP systems:* Yagyu et al. (1997, 2000) designed and tested the performance of a GEHP system. They reported that the total COP is about 1.9 and stated that the COP would be increased to 2.42 if the GEHP system could be pressurized up to 5 MPa. Liu et al. (2005) researched the performance of a GEHP system with different groups of refrigerants. Based on the first law of the thermodynamics, the values of COP and PER of the GEHP were calculated. Li and Zhang (2006) and Li et al. (2007, 2008) designed a hybrid-power GEHP system. Their simulating results of the power system showed that for a conventional GEHP system the maximum and minimum thermal efficiencies of the power system were 33% and 22%, respectively. Compared with the conventional GEHP system, the power system in the novel hybrid-power GEHP system had superior performance with the maximum and minimum thermal efficiencies of 37% and 27%, respectively. In order to reduce the energy consumption of air conditioning system further, Lian et al. (2005) presented the concept of combining of a GEHP and water-loop heat pump system (WLHPS). A design of the new system was introduced through an actual project in China and compared with a conventional air-conditioning system (CACS) and conventional WLHPS (EHP-WLHPS, driven by the electricity) in terms of technical characteristics and payback period. It was found that the payback period of the GHP-WLHPS (driven by the natural gas) was about 2 years when compared with CACS and 2.6 years with EHP-WLHPS on the average.
- (3) *Research on modeling of GEHP systems:* The first modeling of GEHP systems was done by MacArthur and Grald (1989). It was a dynamic model of a vapor compression HP, and the lumped-parameter models were developed for the expansion valve and natural gas engine. Rusk et al. (1990) established a mathematical model consisting of two parts, an engine model and a HP model. The heating season performance factor was calculated by using this model under two different climatic conditions. They also made an economic analysis of two control methods. According to this model under a constant speed operation, the GEHP was more efficient than the electric HP whereas the electric HP was more efficient under variable speed operations. Following this model, Yang et al. (2004) improved a dynamic model with an exhaust gas heat exchanger. Zhang et al. (2005) established a steady-state model. They investigated a waste heat model of the gas engine experimentally and a heat recovery model of the system theoretically.
- (4) *The study on improving control strategies of GEHP systems:* Based on the dynamic model of the GEHP system, Yang et al. (2007) presented an intelligent control simulation to research the dynamic characteristics of the system in the heating mode. The intelligent control model was composed of the prediction controller model and the combined controller model. The results showed that this control method had good control effectiveness and the steady state accuracy of the intelligent control scheme was higher than that of the fuzzy controller. Then Li et al. (2005a, 2005b) developed a cascade fuzzy control strategy for a GEHP. The cascade control strategy which had large time constants and disturbances was effective for the systems, while the fuzzy control strategy was fit for a system, which lacked an accurate model. The performance of the cascade fuzzy control was compared with that of a cascade proportional and integral (PI) control

strategy. The result indicated that the cascade fuzzy control strategy was a stable control system with reduced reaction time and little overshoot in temperature.

Although many investigators have devoted their attention to the system integral energy efficiency and economy of the unit and improving the performance of the GEHP by designing and developing its parts, establishing the models, improving controlling strategies, yet the impact of government policies for extending use of GEHP on the energy structure for a city or country and real-example analysis and experimental research are very limited. Therefore, the capacity characteristics of GEHP are analyzed in this paper, and the relationship between the capacity of GEHP and the heating and cooling loads of buildings has been investigated. The running characteristics of a water-to-water GEHP have been investigated experimentally and the PER of the system has been measured. Based on these analyses and experimental results, the impacts on the requirement and provision of electricity and natural gas during a year and the balance of the seasonal consumption differences of electricity and natural gas for a country between summer and winter simultaneously by using the GEHP have also been discussed. All the above mentioned research achievements are useful for heating/cooling equipment manufacturers, secretary of state for energy and environment, land agents and heat pump researchers. In order to improve the energy consumption configuration effectively and keep the sustainable development of the society, this paper suggested that the governmental incentive policies for promoting use of GEHPs should be formulated in China and some other developing countries.

2. Relationship between the capacity of the GEHP and the heating/cooling loading of buildings

As a kind of high efficiency and energy-saving equipment, GEHP is applied in various buildings to replace the traditional air conditioners and electric-driven HP at home and abroad. The first actual engineering GEHP was installed in the Royal Festival Hall, London (Montagnon and Ruckloy, 1953); The GEHP has been used in gymnasium and restaurant in Switzerland since 1974 and Morgan et al. installed a GEHP system using R22 as refrigerant in Washington Hotel in 1987 (Wang, 2009); After investigating up to 1400 GEHPs used by commercial malls, schools and business buildings in Tokyo, Yokoyama (1992) proposed some suggestion on the GEHP design; in the recent years, new-built buildings with GEHPs are gradually up in China. In order to make a contribution for extending the use of GEHP in buildings, the analysis of relationship between the capacity characteristic of GEHP and heating/cooling load of buildings is presented. In addition, the advantage of GEHP on the capacity adjustment, compared with the ordinary electric-driven HP is also studied.

2.1. Annual heating/cooling load analysis of a building

In this study, a hotel with a total area of 6058 m² in Beijing is taken as an example. It consists of 6 floors and 48 office rooms on each floor. A simulation tool named DestII developed by Tsinghua University is used to calculate the heating/cooling load of the building. Figs. 3 and 4 show the heating/cooling load of the building in a typical year, respectively. It is noted from Fig. 3 that the curve of heating load presents the concave-up parabola curve, and there is no heating load in summer months. From the Fig. 3 we can also see that the heating load decreases quickly from February to April, while, it increases quickly from September to December. On the contrary, as indicated in Fig. 4, it is found that the curve of cooling load presents the convex-up parabola curve.

The cooling load increases quickly from March to June, and it reaches the maximum in July. Soon after, the cooling load decreased quickly.

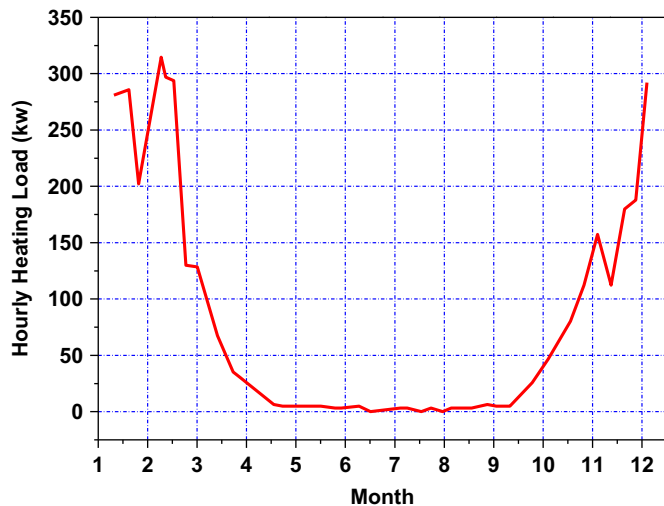


Fig. 3. Hourly heating load for 12 months.

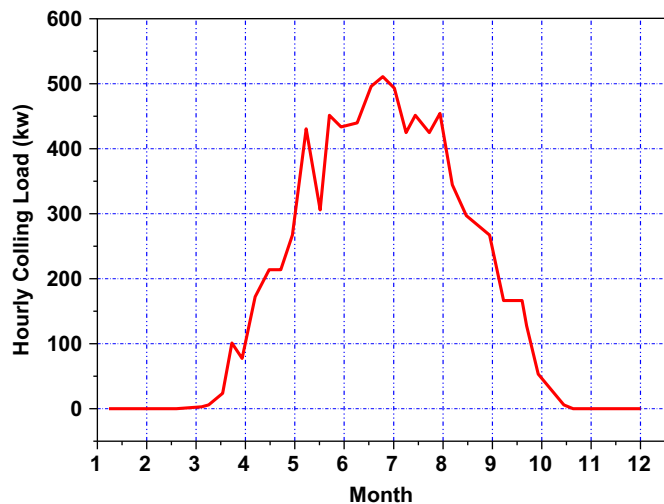


Fig. 4. Hourly cooling load for 12 months.

2.2. Relationship between the capacity of an ordinary electric-driven HP and the cooling load of building

The heat capacity of ordinary electric-driven HP and the heating load of building change along with the variation of the outdoor temperature, which is shown in Fig. 5. From Fig. 5, we can see that the heating load of building decreases with the increase of the outdoor air temperature, whereas the heating capacity of the ordinary electric HP increases with the increase of the outdoor air temperature because the electric HP is running at a constant compressor rotary speed. As presented in Fig. 5, we can also see that the capacity of the HP and the heating load of building have an intersection at a certain temperature, that is to say, there is an equilibrium point where the matching relationship between the heating capacity of the HP and the heating load of the building reaches balance. When the ambient temperature is higher than the temperature of equilibrium, the capacity of the HP is larger than the heating load of building. Conversely, when the temperature is below the balance point, the capacity of the HP is smaller than the heating load of building. Then we have to adjust the capacity of the HP by cycling the compressor, and it will result in energy losses and temperature fluctuations. There is almost always an imbalance between the heating supply and the heating requirement if the compressor of the ordinary electric-driven HP is only operated at a constant rotary speed. In order to achieve the optimum capacity of the HP system under different outdoor temperatures, more balance points are needed and the capacity of the HP system should be adjustable.

2.3. Capacity adjusting method of an ordinary electric-driven HP unit

In regard to the ordinary electric-driven HP unit, the following methods can be used:

- *On-off control method*: This is a simple method. The capacity of the electric-driven HP is adjusted by controlling the compressor on-off, and it belongs to the method of discontinuous capacity regulation.
- *Off loading control method*: It is a method of adjusting the capacity of an electric-driven HP to meet the heating/cooling load by reducing the number of compressors or increasing the number of vacancy load cylinders of compressor.
- *The opening and closing schedule of intake valve control method*: The essence of this method is to control the piston swept

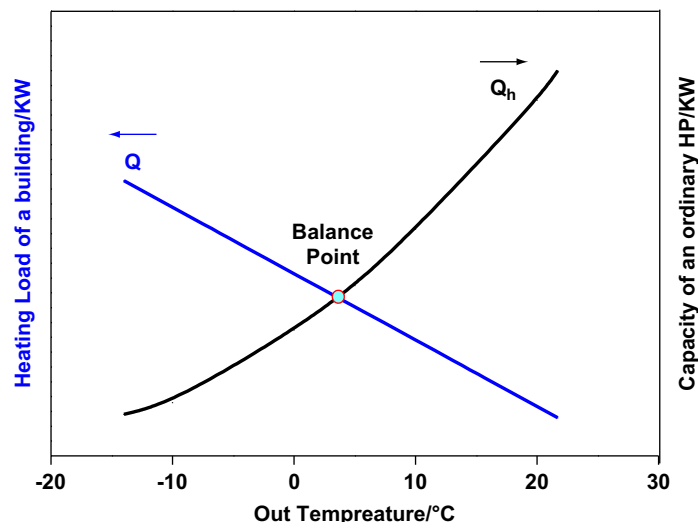


Fig. 5. Heating characteristic of an ordinary electric-driven HP.

volume of compressor artificially, thus, the capacity of the electric-driven HP can be changed continuously.

- **Variable-speed control method:** The volume of piston swept could be changed by altering the rotary speed of compressor, in regard to the ordinary electric-driven HP unit, which can be achieved by a frequency converter.

2.4. Capacity characteristics of a GEHP

As for the GEHP, the capacity of a GEHP can be regulated by altering the rotary speed of the compressor and there are two ways to make it happen. One is changing the mechanical gear ratio of transmission mechanical, and the other is to change the rotary speed of the prime mover (the engine) directly. Compared with the above mentioned methods of capacity adjustment, the method of adjusting the rotary speed of compressor and engine of the GEHP can not only reduce the on-off loss, but also improve the efficiency of the system. Furthermore, it is convenient to realize stepless speed regulation in a large range. The capacity of the GEHP can be perfectly matched with the heating/cooling load of buildings by changing the rotary speed of the engine and compressor.

The rotary speed of the engine as well as the capacity of the GEHP can be controlled by adjusting the quantities of the natural gas provided to the gas engine and achieved the stepless regulation. The transmission mechanism between the gas engine and heat pump is not only simple in construction but also efficient in performance. Therefore, it is an excellent way with great developmental potential for capacity control of the GEHP system.

The running characteristics of a GEHP at the different gas engine speeds are illustrated in Fig. 6. The phrase ' $n1\text{ rpm}$ ' means that the number of revolution of the GEHP is $n1$ per minute. And ' $n2 > n1$ ' means the engine speed of the former is faster than the latter. As shown in this schematic diagram, we can analyze qualitatively that with the change of outdoor temperature, the heating capacity of the GEHP can be able to meet the heating load requirements of buildings by adjusting the rotary speed of the engine and compressor. When the GEHP running in winter, the heating load of buildings decreases with the increase of the outdoor air temperature. At this time, the capacity of the GEHP should be reduced by controlling the engine at a suitable lower rotary speed. When the outdoor air temperature is reduced, we need to increase the rotary speed of the compressor to meet the increasing demand of the heating load. The heating and cooling loads of buildings change along with the outdoor air temperature during the year, and in order to achieve the optimum capacity of

the GEHP, we can change the capacity of the GEHP by controlling the rotary speed of gas engine to meet the heating and cooling load of buildings. In addition, it is well known that the consumption capacity of the natural gas changes with the rotary speed of the gas engine, therefore there must be different optimum consumption capacities of the natural gas under different outdoor temperatures and the more accurate relationship among them could be concluded from the experimental results.

Energy Conservation Law of the People's Republic of China, issued and taken effect in 2008, is playing an important role in building energy efficiency, which is good for promoting the use of GEHP. And there is no doubt that the *energy conservation design standard for residential building* and *Regulation of civil building energy saving* (Yang et al., 2010) could improve the competitiveness of GEHP. Owing to its advantage and development potential, the experimental research is necessary.

3. Experimental verification of the running characteristics of a water to water GEHP

3.1. Experimental apparatus

The components of the experimental apparatus is introduced in detail, which would be helpful for the researchers and manufacturers who are interested in the technology of the GEHP, and the suppliers and the distributors who are interested in the price of the GEHP.

As illustrated in Fig. 7, a water to water GEHP system is mainly composed of a vapor compression HP system, a heat source system, a data acquisition and controlling system, and a gas engine system. The core of GEHP is a vapor compression HP system driven by a gas fueled internal combustion engine instead of an electric motor. And it includes an open type compressor, a condenser, an expansion valve and two evaporators. A receiver is also used in the system to balance the differences of the refrigerant in the heating and cooling mode. The CB52-112HX plate heat exchanger is used for condenser, and the CB52-40HX plate heat exchanger is used for the evaporator. The stepless speed regulation of the open type compressor can be realized by controlling the engine rotary speed when the speed lies between 500 and 3000 rpm. The TCLE7-1/2MC thermostatic expansion valves have been introduced into the system. The gas engine system consists of a fuel supply system, a gas engine, a heat recovery system of smoke evacuation and cylinder heat recovery system.

The data acquisition and controlling system is composed of thermoelectric couple, pressure transducer, rotating speed transducer, flow rate transducer, voltage transducer, electric current transducer, PLC module, rotating speed controller, expansion valve controller and water outlet temperature controller. The outer heat source system is composed of a condenser loop and an evaporator loop, while the evaporator loop is mainly comprised of a chilled water tank, evaporator, pumps, and related piping. The condenser loop consists of cooling water tank, condenser, cylinder liner heat exchanger, exhaust gas heat exchanger, outdoor fan coils, pumps, and relevant piping. The exhaust gas heat exchanger is a horizontal shell and tube type. The conduct of the test is referred to the relevant ASHRAE Standard and ARI550-98, and adjusting the temperature of different high and low heat source. The natural gas consumption can be tested under the different engine speeds.

3.2. Analysis of the experimental results

The relationship between the natural gas consumption and the rotary speed of gas engine is shown in Fig. 8. It could be seen that

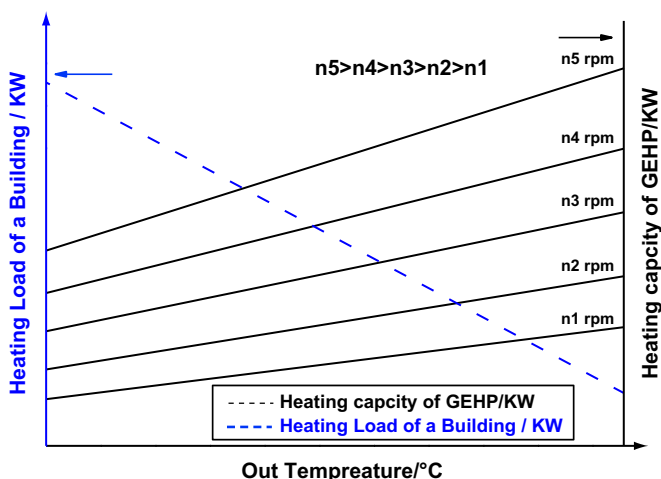


Fig. 6. Capacity characteristic of the GEHP as a function of engine speed.

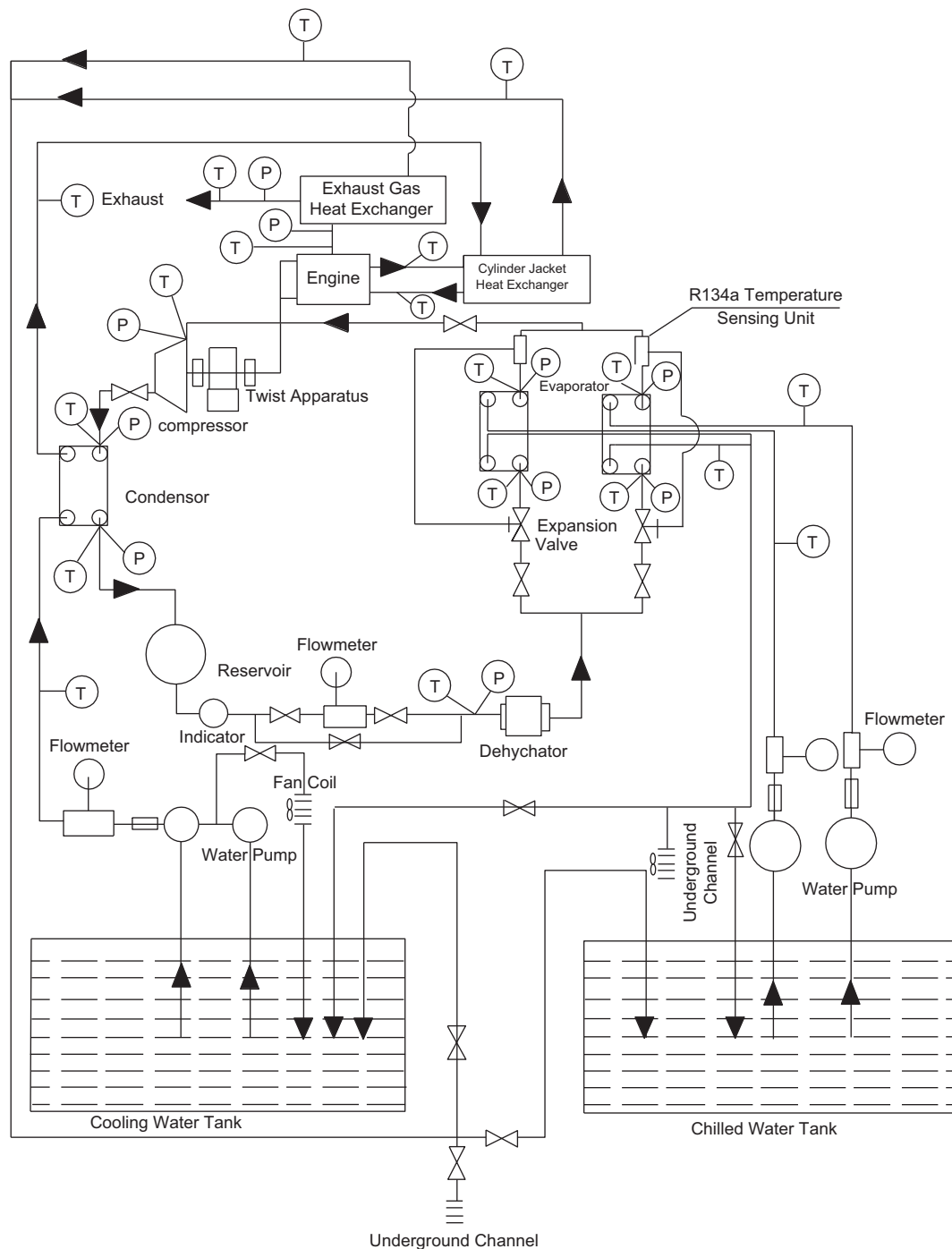


Fig. 7. Schematic of the water-to-water HP driven by a natural gas engine.

the consumption of natural gas increases almost linearly as the rotary speed of the gas engine increases. In Fig. 8 The unit ' $\text{Nm}^3 \text{h}^{-1}$ ' means the volume of gas consumption per hour under the standard state (a standard atmospheric pressure and 0°C). According to the experimental data described in Fig. 8, we can calculate the consumption of the natural gas when the speed of engine lies between 1750 and 5250 rpm.

As indicated in Fig. 9, we can see that with the change of the engine rotary speed, not only the condensation heat and the cooling capacity of system, but also the recovery capacity of exhaust heating from the engine and the total recovery heating are all changed properly. That is to say, when the heating/cooling load of the system increase, we can meet it by increasing the

rotating speed of the engine. Therefore, the target of the variable capacity control can be achieved well.

Fig. 10 shows the relationship between COP/COP_c of the GEHP and the rotary speed of gas engine when the evaporating and the condensing temperature are 15 and 44°C , respectively. The abbreviations of COP_c can be defined:

$$\text{COP}_c = \frac{\text{cooling capacity of the system}}{\text{Input power of compressor}} \quad (3)$$

We can see that the COP and COP_c of the system increase as the rotary speed decreases while the COP and COP_c of the GEHP varies very little with the load fluctuation. In other words, even if the load changes greatly, the system can also run in a stable and

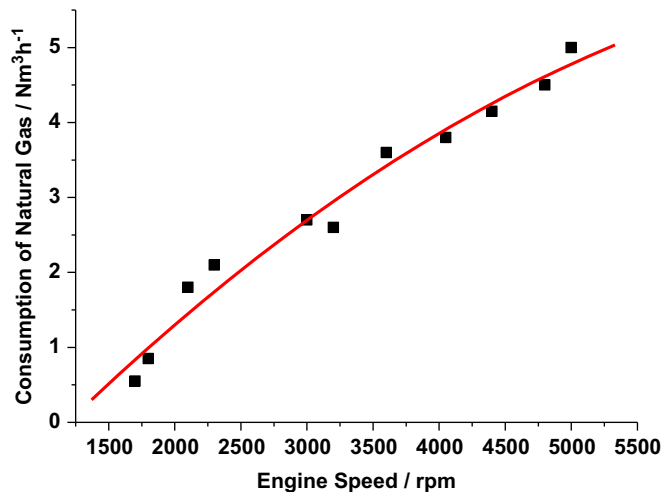


Fig. 8. Relation between consumption of natural gas and speed of gas engine.

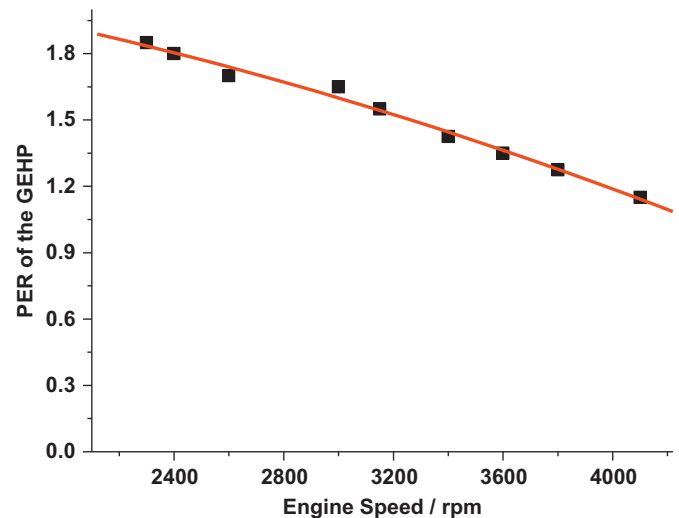


Fig. 11. Relation between PER of GEHP and speed of gas engine.

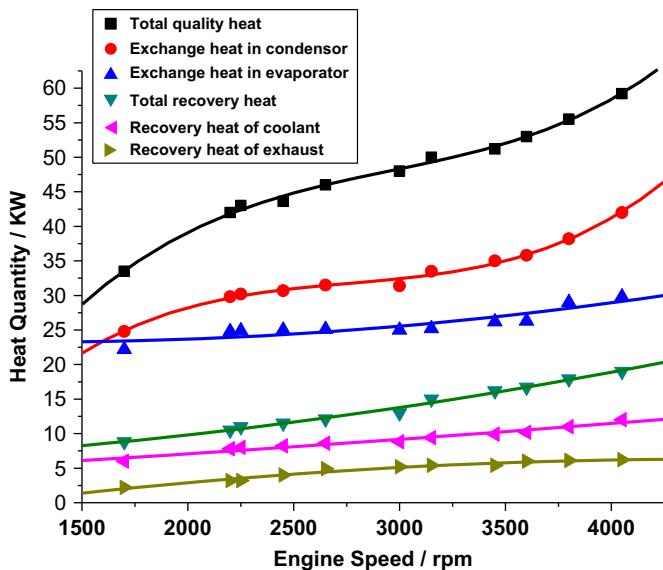


Fig. 9. Relation between heat quantity and speed of gas engine.

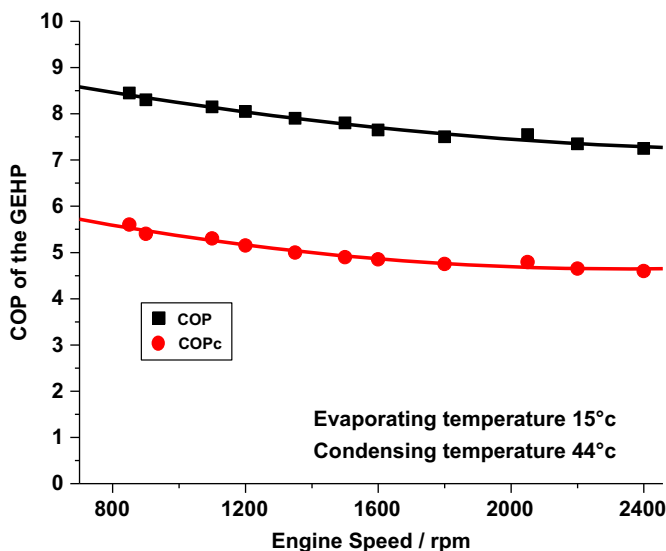


Fig. 10. Relation between COP of GEHP and speed of gas engine.

efficient mode. It can be concluded that the GEHP has a good speed control performance.

From Fig. 11, we can see that the PER of the system decreases with an increase of the rotary speed of the gas engine. That is to say, it is not good for energy-savings when operating the engine at a higher speed and also, the operating cost will increase too.

To sum up, the experimental results indicate that if the climate conditions changed, the capacity of the GEHP could meet the heating/cooling load of the building well by controlling and adjusting the rotary speed of the gas engine. Therefore, the authors recommend extending use of the GEHP due to its advantage of better flexibility, high efficiency and environmental conservation.

4. Impact on the requirements and provisions for electricity and natural gas by extending use of the GEHP

4.1. Seasonal consumption differences of electricity and natural gas between summer and winter

Owing to its convenience, it is the electricity that is the first choice energy for driving air conditioners. Taking Shanghai as an instance (Long et al., 1998), the electric air conditioners account for 82.3% and 43.7% of all types of air conditioners in summer and winter, respectively. Such a high proportion of using electric air conditioners leads to an imbalance of electricity consumption between summer and winter. Also using Shanghai as an example (Dai, 2003), the highest electrical load is 10.476 million kW in the summer of 2000, and the electrical load which is used by air conditioners is 3.9 million kW, which takes up about 37.2% of all the electrical load. However, the electrical load is 7 million kW in the winter of 2000, which is only about 66.8% of that in summer. Likewise, there also exists an imbalance of natural gas consumption between summer and winter. The natural gas load is the lowest in summer and the highest in winter, mostly as a result of the natural gas used in gas-fired boilers for heating. For instance, in Shanghai city (Dai, 2003), the load of average natural gas consumptions is about 4.7 million Nm^3 per day in August of 2000, but in January of the same year, it is 6.29 million Nm^3 per day. That is to say, in summer the load of average natural gas consumptions is only about 75% of that in winter. The imbalance of natural gas consumption between summer and winter leads to an additional cost for storing the excess natural gas in summer.

4.2. The considerable suggestions of extending the use of the GEHP to reduce seasonal consumption differences of electricity and natural gas

Summarizing the above mentioned seasonal consumption differences of electricity and natural gas between summer and winter, which can be concluded as follows: in summer, the electricity consumption reaches its peak mainly due to the large amount usage of electric air conditioners while the natural gas demand drops drastically because of the decreasing demand of heating. In winter, the natural gas consumption reaches its peak due to the usage of gas-fired boilers, which are low energy efficiency and spend much more gas than the GEHP for the same heating requirements. The governmental incentive policies for promoting use of GEHPs to replace the gas-fired boilers and electric air conditioners for heating and cooling should be formulated in China and some other developing countries.

The following incentive policies can be taken into consideration by governments:

- (1) setting a lower price of the natural gas for the GEHP users in summer;
- (2) setting a higher price of the electricity for the electric air conditioners users in summer, especially, June–August;
- (3) setting a higher price of the natural gas for the gas-fired boilers users in winter.

Price is a sensitive factor for customers in market economy countries, which could influence citizen's consumption propensity. Many governments take the commodity price as a kind of economic readjustment means and it is indeed workable.

- (4) Reducing the taxes of the companies which produce GEHPs and associated components, thus both the manufacturers and consumers could benefit from the decreasing production cost;
- (5) Providing low-interest loan for the consumers who would like to buy a certain amount of GEHPs. In addition, the hire-purchase plan of interest-free is also available for accelerating the extending use of GEHP;
- (6) Establishing related environmental policies and encouraging the usage of the natural gas rather than the coal, such as *China's National Climate Change Program*;
- (7) Funds for supporting the universities and institutions to carry out the research of GEHP technology should be established.

Then, we can mitigate the electricity demand consumption peak and increase the natural gas demand in summer; reduce the gas consumption peak in winter and balance the load of natural gas and electricity between summer and winter simultaneously, at the same time, reduce the consumption of coal and mitigate the environmental pollution. Consequently promoting the usage of the GEHP in China could play an important social and economic role by balancing the demand and provision of electricity and natural gas, adjusting the energy consumption structure and improving environmental quality.

4.3. The impact on the consumption of the natural gas by promoting use of the GEHP

Extending the use of the GEHP will impact the consumption of natural gas but the extent of the influence is relevant to many factors. Firstly, it could be relevant to the structure of the urban fuel consumption. Taking Beijing for example, according to the national development planning, the coal-fired boilers which were used for heating in the urban area had been replaced by gas-fired boilers before the 2008 Beijing Olympic Games but nowadays many gas consumers are bearing the cost of paying for the large amount of

gas cost for heating every year. The usage of the GEHP can reduce the natural gas consumption because of its higher energy efficiency and also can save money for consumers. Secondly, it is relevant to the local climatic conditions. In the northern region, there is a relatively long period of heating, and in the southern region, there is a relatively long period of cooling. The proportions of natural gas consumption in different regions are different in winter and summer. Therefore note that: different price and application policies are suitable for different regions, while implementing the realistic measures according to local conditions.

4.4. Adjustment results in different seasons during a year

Supposing the efficiency of electric power supply is 33%, the thermal efficiency of the gas engine is 30%, COP of the GEHP is 3.6, the efficiency of a gas boiler is 85% and 60% of waste heat of the gas engine can be recovered, and then the PER of the GEHP is 43.3% higher than the gas boiler (Yang et al., 2001).

Using GEHPs to replace gas-fired boilers in cities can save a large amount of natural gas consumption in winter. In order to analyze the regulatory effect of the usage of GEHPs on the load of natural gas quantitatively, the building mentioned above is taken into consideration: According to the matching relationship between heating/cooling load of the building and the capacities of the GEHP, the distribution curves of the needed capacity of the natural gas supply can be obtained when the gas-fired boilers are replaced by GEHPs to offer the 100%, 75%, 50% and 25% of the heating loads in a year. The curves are shown in Fig. 12.

As illustrated in Fig. 12, there would be no natural gas consumption for the building in summer if the gas boiler and electric air conditioner were used for heating and cooling, but there exists $3.7 \times 10^5 \text{ N m}^3$ difference of natural gas consumption between winter and summer. If the 50% of heating load for this building was supplied by the GEHP instead of the gas-fired boiler in winter and also use the GEHP for cooling in summer for this building, the difference of natural gas consumption between summer and winter would be only 10^5 N m^3 .

As presented in Fig. 12 if the gas-fired boilers and electric air conditioners are replaced by GEHPs in some percentage, the consumptions of the natural gas are increased in summer and decreased in winter, and then we can narrow the gaps between the requirement and provision of the electricity and natural gas efficiently. After further calculation, we can conclude that if 64% of the heating load for this building was supplied by the GEHP instead of the gas boiler in winter and also using the GEHP for

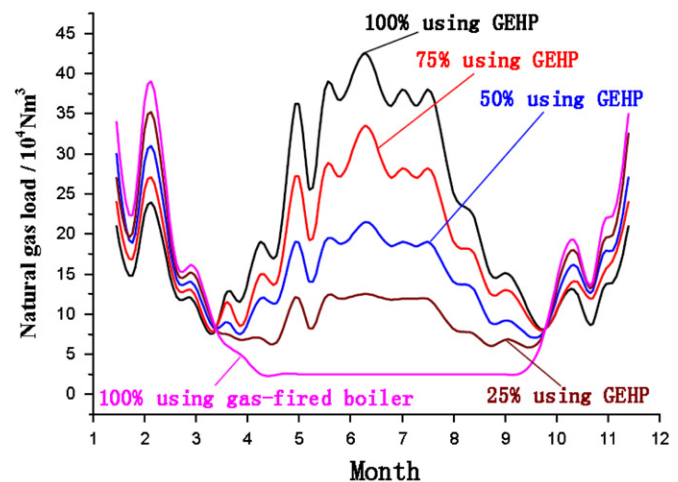


Fig. 12. Natural gas load of a building used by gas-fired boiler and a certain percent of GEHPs.

cooling in summer, the largest consumption of natural gas would be the same in winter and summer and the annual largest consumption of natural gas would be decreased substantially. At the same time, as a result of using the GEHP for cooling in summer, the power fluctuation which is caused by the mass use of electric air conditioners could be relieved sharply. As revealed in Fig. 13, the electrical load is decreasing greatly in summer, and the effect is obvious.

4.5. A real example about the consumptions of natural gas and electricity in Beijing City

We take the consumptions of natural gas and electricity in Beijing City during the year of 2000 as an example. From statistics, the total natural gas consumption for this year was $10.9 \times 10^9 \text{ Nm}^3$ and the heating load proportions of each month in the year are shown in Table 2 (Cheng, 2002).

Supposing the loads of heating and cooling are 70 and 110 W/m^2 , respectively (Yang et al., 2001), the needs of the natural gas and electricity which are used for offering heating and cooling monthly are shown in Figs. 14 and 15 if we only used gas-fired boilers for heating and electric air conditioners for cooling. And also, in these figures, the curves of the 100% and 50% of heating loads supplied by the GEHP to replace the gas boiler in winter and also using the GEHP for cooling in summer are obtained.

From the figures, we can see that under the condition of extending use of the GEHP for heating and cooling, compared with using the gas boiler for heating, the consumption of urban natural gas can be reduced greatly in winter; compared with using the electric air conditioner for cooling, the electrical load can also be reduced in summer. If the 50% of heating load was supplied by the GEHP instead of the gas-fired boiler in Beijing City in 2000, the natural gas load would be kept balance basically between winter and summer. The largest natural gas consumption of the year

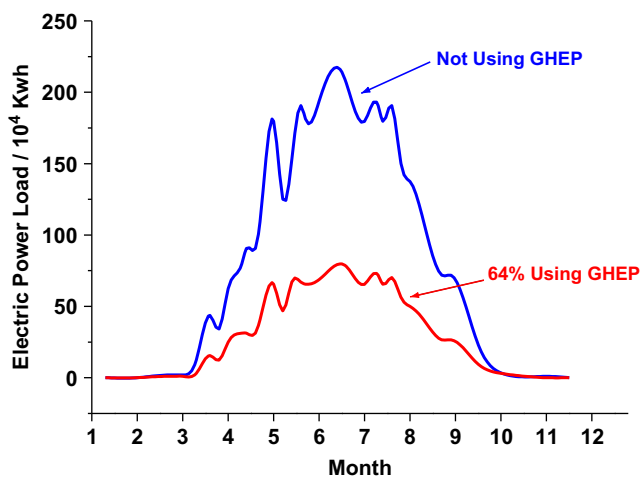


Fig. 13. Electric power load of air conditioners which is replaced by a certain percent of GEHP.

Table 2
Heating load proportion of each month in Beijing during the year of 2000.

Month	1	2	3	4	5	6
Proportion	0.3	0.15	0.1	0	0	0
Month	7	8	9	10	11	12
Proportion	0	0	0	0	0.1	0.35

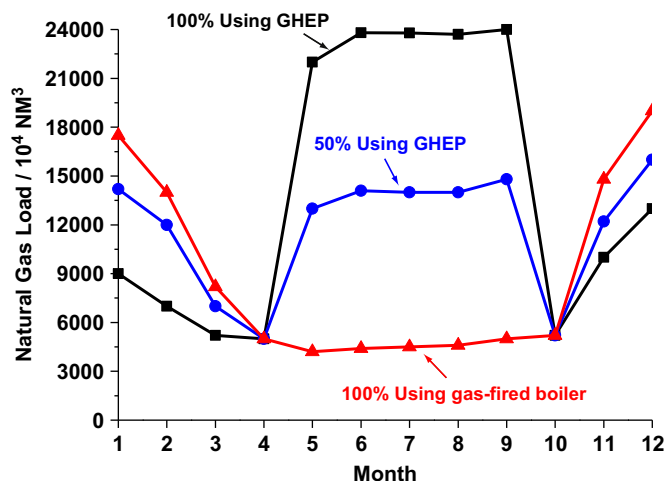


Fig. 14. Load of natural gas for heating and cooling in Beijing.

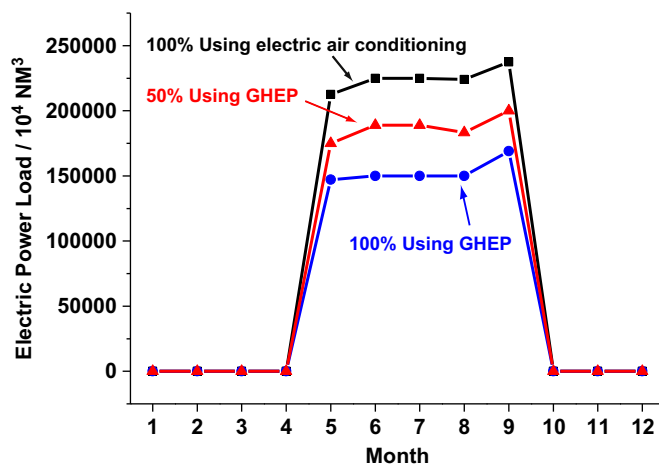


Fig. 15. Load of electric power for heating and cooling in Beijing.

would be reduced about 40%, and the largest electrical load used for air conditioning in summer would also be reduced about 50%.

5. Policies extending use of GEHPs

5.1. Environmental friendly policies

Nowadays, the HP and air conditioner systems are mainly driven by electricity, and about 73% of the electricity is generated by burning coal in China (Cen, 2006). The burning of coal will create a lot of atmospheric pollutants such as CO_2 , NO_x , SO_x , soot and all of them are bad for our environment. Reducing those pollutants will increase the cost of power production. Therefore, the advantages of the GEHP in saving energy and reducing pollutants become more pronounced. So many governments have made environmentally friendly policies of energy use. For instance, there are two definite principles of energy use in the *Outline of Chinese Eleventh Five-Year Plan*, which are, Energy Saving and Emission Reduction. Thus, there will be a big market for promoting the use of GEHP. Owing to its advantages in balancing electricity and natural gas demands between summer and winter effectively, mitigating the electricity peaks and adjusting the energy configuration, each government, especially the Chinese government, should provide more economic supports in

the production and application of the GEHP and plan to promote more policies extending use of the GEHP.

5.2. Projects of the gas pipeline and sufficient natural gas supply policies

In China, the projects of West–East Gas Pipeline (transmitting natural gas from the west to the east region) and the urban natural gas pipeline networks will expand the scope of natural gas application, and balance supply and demand of natural gas between East China and West China effectively. As one of the key items of West Development Strategy, the project of Sebei-Xining-Lanzhou Gas Pipeline will make great contributions to environmental protection and economic development. The project of Sichuan-to-East Gas Transmission Pipeline which is one of the significant projects in *Eleventh Five-Year Plan (2006–2010)* has been put into operation. And a number of gas pipelines are under construction now. What's more, China has already signed some agreements with its neighboring countries such as Russia, Kazakhstan and Burma to import natural gas. All of these projects will provide the necessary guarantee for a sufficient natural gas supply for extending use of the GEHP.

5.3. Sustainable development and security policies

For major cities in China, the construction and operation rights of the urban natural gas networks have been strictly controlled by the central government and private or foreign companies are prohibited from engaging in natural gas exploitation. The government could not invest enough money to renew or build more new natural gas pipelines and other equipments quickly. An economically feasible suggestion of relaxing restriction of foreign or private capital will be a good way to solve these problems, and also, it could form the competition mechanisms in the natural gas industry. Therefore, Chinese government would put forward some new policies to eliminate the backward natural gas enterprises and ensure a steady supply of natural gas. Some other new policies about security should also be proposed to establish a proper controlling and monitoring system to insure security of the natural gas supply and utilization. All of those policies mentioned above are consistent with the Sustainable Development and Harmonious Society and it is good for extending the use of the GEHP.

5.4. Reasonable pricing policies

Under the unbalance condition of the electricity and natural gas consumption between summer and winter, governments should put forward some lower summer-gas price and higher summer-electricity price policies to encourage natural gas consumption rather than electricity consumption in summer. By this means, it would reduce the cost for storing the excess natural gases and ease the power shortages in summer as a result of the use of a great number of electric air conditioners.

All of the above mentioned policies are suitable for extending the use of the GEHP. It could improve the energy consumption structure and make a significant contribution to relieve the global warming.

6. Prospects of GEHP technology

Above all, the usage of the GEHP can balance the natural gas requirements between summer and winter, and also decrease the electricity consumption in summer as well as reduce the air pollution simultaneously. If gas-fired boilers are replaced by the

GEHP at a certain proportion, the maximal natural gas consumption in summer will be equal to that in winter. There are two obvious advantages for extending use of the GEHP. One is to pare electric power peak in summer, and the other is to avoid imbalance of natural gas load between summer and winter. Therefore, promoting the use of the GEHP can play important social and economic roles by balancing the consumption of the electricity and natural gas between summer and winter, mitigating the electricity peaks and adjusting the energy consumption structure and improving environmental quality. Consequently, this technology are enjoying a boom in China and some other countries and some research achievements have been gotten in recent years, which promote the application of GEHP. On the other hand, the advantages of GEHP also evoke a strong attraction to the customers. Therefore, the GEHP technology will have a bright tomorrow.

7. Conclusions

Firstly, the imbalance of the urban electricity and natural gas consumption between summer and winter is result from the large number of electric air conditioners and gas-fired boilers used in summer and winter, respectively. Extending the use of the GEHP will benefit adjusting the seasonal loads of the electricity network and the natural gas network.

Secondly, except for the balance point, the heating and cooling capacity of the ordinary electric-driven HP with a constant compressor rotary speed are always unequal to the heating and cooling loads of buildings. That is to say, there is always an imbalance between the heating and cooling supply and the requirements. In contrast to the GEHP, the electric-driven HP is not energy-efficient.

Thirdly, the running characteristics of a water-to-water GEHP have been investigated experimentally and the PER of the systems was measured. The experimental results indicate that the capacities of the GEHP can meet the heating and cooling loads of buildings well with climate variation by controlling and adjusting the rotary speed of the engine in the GEHP system. The GEHP has great developmental potential for both saving energy and helping to protect the environment.

Fourthly, extending the use of the GEHP will have positive environmental impacts by reducing the usage of coal in China for producing electricity. Promoting the usage of the GEHP in China and some other developing countries can play an important social, economic and environmental role.

Finally, in order to improve energy efficiency, environmental quality and energy consumption structure effectively, the government should provide incentive policies for extending the use of GEHP in major cities. It is consistent with the opinion of Sustainable Development and Harmonious Society.

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